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THERMAL HYDRAULIC ANALYSIS OF IRIS REACTOR COILED TUBE STEAM GENERATOR

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ABSTRACT

In this paper the thermal hydraulic analysis of IRIS reactor coiled tube steam generators is addressed. The main phenomena to be investigated are identified, the most promising computing tools needed for the analysis are selected and the main computational challenges are assessed. This analysis indicates that the current tools are adequate to elaborate the data to be obtained in the forthcoming experimental campaign needed to validate the design of the IRIS reactor steam generator.

Key Words: Thermal-Hydraulics, two-phase flow, coiled tube steam generators, parallel channel stability.

1. INTRODUCTION

IRIS (International Reactor Innovative and Secure) is a light water cooled, 335 MWe power, International Near Term Deployment nuclear reactor which is being designed by an international consortium as part of the US DOE NERI program [Ref.1]. IRIS features an integral vessel that contains all the major reactor coolant system components, including the reactor core, the steam generators and the pressurizer. The steam generators are eight once-through coiled tube independent units located in the annular space between the core barrel and the reactor vessel wall. Each module consists of a central inner column which supports the tubes, with the lower feed-water header and the upper steam collector connected to the reactor vessel. Secondary fluid boiling takes place within the tubes while the primary reactor cooling water cross flows through the tube bundle [Ref.2]. Ansaldo Nucleare of Genova-Italy, Ansaldo-Camozzi Nuclear and Special Components of Milano-Italy and the Politecnico di Milano-Italy are the members of the IRIS consortium in charge of the design of the steam generator, which is one of he most innovative components of IRIS.

Helical coil tube bundles are capable of high thermal performance, due to their large surface area per unit volume, can accommodate thermal expansions without excessive mechanical stress and have high resistance to flow induced vibration. The major concern with integral steam generators located inside the reactor vessel is the fact that the steam generation takes place inside the tubes, a condition potentially prone to parallel channel flow instability. This concern, though common to all once-through designs, could be somewhat more severe in the IRIS case due to the very high ratio of tube length to tube diameter. On the other hand, coiled tube bundles are more flexible than straight ones, thus coiled tube steam generators can be expected to be less vulnerable, from the mechanical point of view, in case of unstable flow occurrence.

Helical coil steam generators are a proven design that has operated successfully in various reactors, including the French Liquid Metal Fast Breeder Reactor Superphenix. There is also a ten years operating experience (1968-1979) of the PWR powered German Nuclear Ship Otto Hahn, equipped with a 38 MWth coiled tube steam generator. Besides, Ansaldo Nucleare built and tested a coiled tube steam generator mock-up of 20 MWth whose geometry closely approximates the IRIS reactor steam generator [Ref.3]. In addition, coiled tubes are widely used worldwide in heating and refrigerating plants. Notwithstanding such experience, a basic lack of open literature on the subject and several unique features of the IRIS steam generator concept prevent the use of standard analysis procedures and require the adoption of ad-hoc modeling tools.

Scope of the present paper is to address the thermal hydraulic analysis of the IRIS steam generator, in order to identify the phenomena to be investigated, to select the computing tools necessary for the analysis and to highlight the corresponding modeling and numerical concerns to be addressed.

2. MAIN THERMAL HYDRAULIC PHENOMENA AND MODELING

At this stage, the analysis of IRIS steam generator relies on existing computing tools, with well known limits and capabilities, that according to necessity will be tailored and upgraded to get a satisfactory approach to the problem on hand.
The current design parameters of one steam generator module are reported in Table I.
A brief description of the analyses performed to establish the thermal hydraulic design is reported in the following.

Table I. IRIS steam generator design data and full power operating conditions

Rated Power [MWth]	125	Primary Inlet Temperature [K]	601.5
Tube External Diameter [mm]	17.46	Primary Outlet Temperature [K]	565.1
Tube Internal Diameter [mm]	13.24	Feed-water Temperature [K]	497.0
External Shell Inner Diameter [mm]	1640	Steam Temperature [K]	590.1
Internal Shell Outer Diameter [mm]	610	Primary Pressure [MPa]	15.5
Tube Bundle Average Length [m]	32.0	Steam Outlet Pressure [MPa]	5.8

2.1. External Flow

This analysis addressed a vertical downward cross flow of a single phase liquid through a coiled tube bundle. The system code RELAP was selected for preliminary analysis, both in steady and transient state. The code adopts a one-dimensional finite volume approach. The built-in empirical correlation for cross flow comes out to be quite accurate, while the pressure drop prediction can be accurately tuned by means of classical literature results [Ref.4]. As a rule of thumb, a few tens of volumes are enough to get accurate and stable predictions (Fig. 1 through 4 refer to steady state full power operation of IRIS steam generator).

For detailed three dimensional analysis we turned to the CFD finite volume approach computing program FLUENT, capable of accurate and detailed predictions. The number of volumes required depends on the extension of the portion of the steam generator to be simulated and on the degree of accuracy required. It ranges from thousands to a few hundred thousands cells.

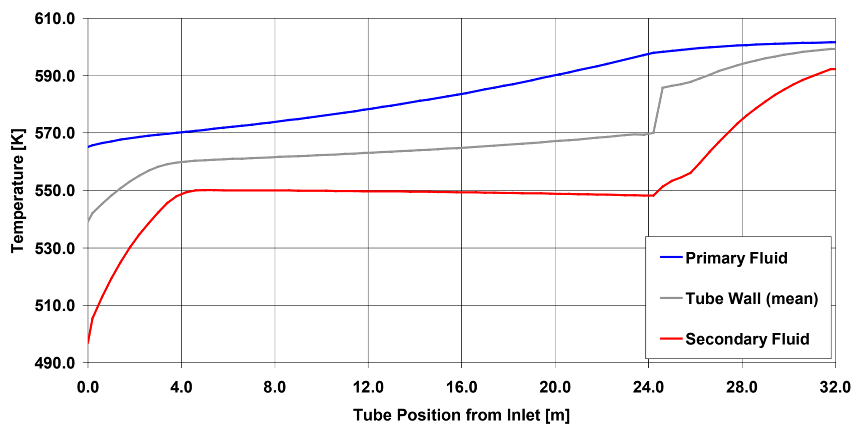

Figure 1. Primary side, secondary side and tube wall temperature profiles for the Steam Generator nominal conditions.

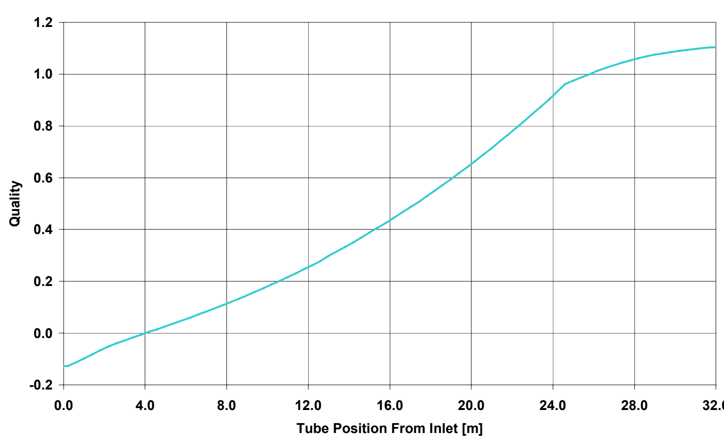

Figure 2. Quality profile for the Steam Generator secondary side.

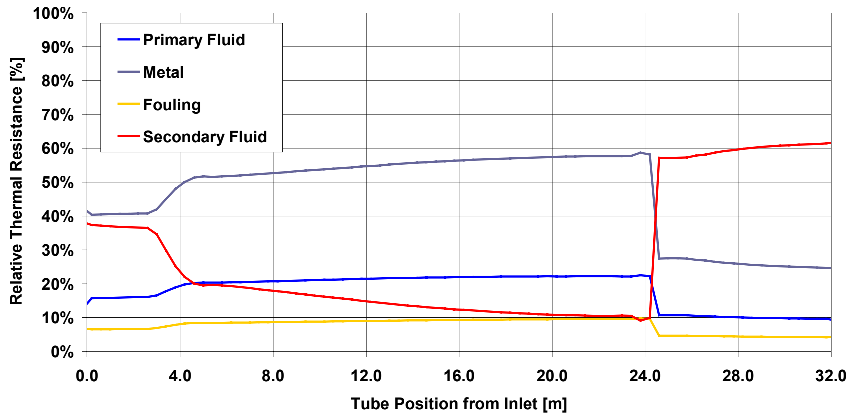

Figure 3. Thermal resistance profiles in the Steam Generator module.

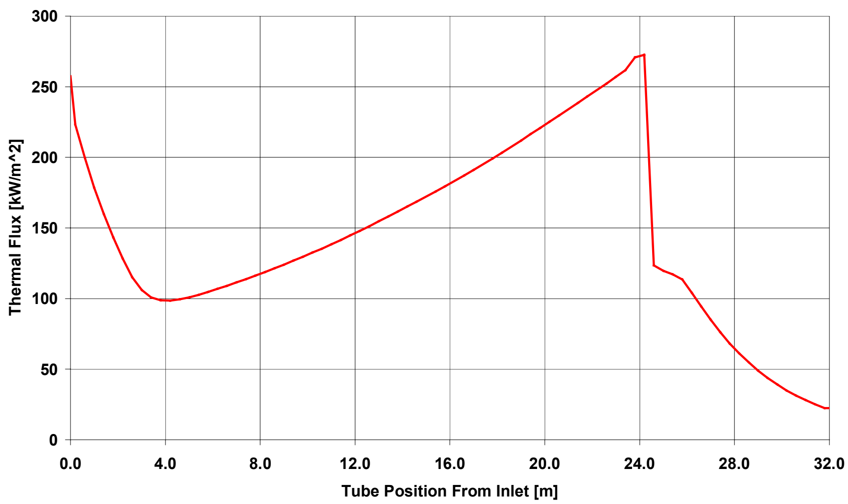

Figure 4. Thermal flux profile through the tube wall (inner surface).

In Fig. 5 a CFD analysis of the secondary spiraling flows that develop within a single phase fluid flowing in a coiled channel is reported; Fig. 6 shows a CFD analysis of the cross flow in the header zone, where the tube bundle is connected to the header. To a certain extent, CFD predictions can be used to adjust the one dimensional RELAP model and provide more details of the flow dynamic itself.

2.2. Internal Flow

This analysis modeled a system of coupled boiling channels of coiled shape, fed with single phase sub-cooled liquid at the lower inlet and delivering superheated steam at the upper outlet. The system code RELAP was again selected for preliminary analysis, both for steady and transient conditions. From a fluid dynamics point of view the main difference between a straight and a coiled tube is the appearance in the latter of a centrifugal force acting on the flowing fluid, due to the curved shape of the channel. In single phase flow the net effect of such a centrifugal force is to induce secondary flows in the flowing fluid of spiraling shape in the plane of the tube axis. These secondary flows promote the mixing of the fluid, thus increasing the heat transfer capability at the expense of higher pressure drops [Ref.5].

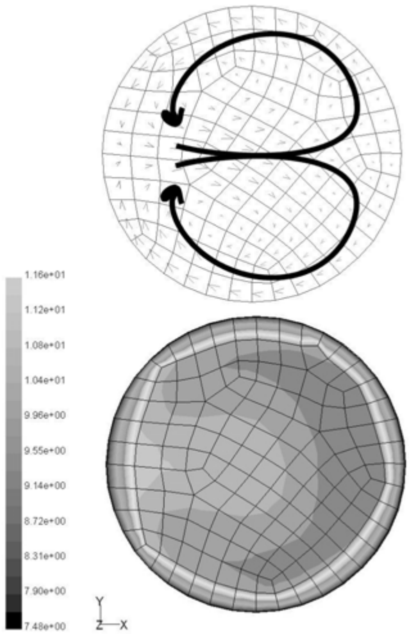

Figure 5. CFD simulated secondary flows into the tube helix (tube axis is vertical).

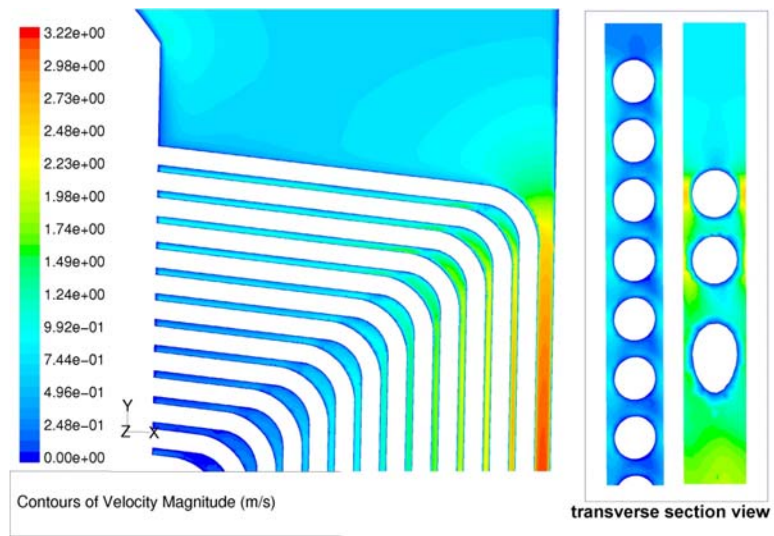

Figure 6. CFD analysis of the primary cross flow on the tube bundle (header connection).

In two phase flow the main effect of the centrifugal force acting on the boiling mixture should be to keep the tube wall wet up to very high qualities, shifting the dry-out toward vapor saturation and reducing the extension of the post dry-out two phase flow region. Since the tube wall is kept wet for the most part of the boiling channel, the heat transfer capability is expected to increase, with respect to an horizontal straight tube, especially in the high quality region of the channel [Ref.6,7]. As a rule, an increase in pressure drop should follow an increase in heat transfer. A literature survey revealed a somewhat incomplete picture as far as heat transfer and pressure drop prediction in coiled tubes are concerned, since considerable scatter emerges among the correlations proposed by different researchers [Ref.8]. As a matter of fact, a straight horizontal tube approximation for two phase prediction appears the obligated solution at this stage of the analysis. Anyway the approach could be not conservative and limited in flow dynamics simulation capability.

For the time being, the 1-D system code RELAP has been adapted by arbitrarily extending the validity of the built-in flow regime map from the straight horizontal tube to the helical coil configuration. Another approximation has been the adoption of heat transfer and pressure drop correlations valid for horizontal straight tube suitably multiplied by corrective factors to obtain design values. A modeling activity is under way, aiming at modifying the 1-D system code in order to duly simulate the correct fluid dynamics of the tube bundle. This goal can be obtained by inserting numerical correlations taken from literature when available or set up through an ad-hoc experimental campaign.

As far as numerical discretization and stable operation is concerned, all the channels can be conveniently lumped into a single average tube or into a few representative tubes. As a rule of thumb, a number of volumes equal or higher than the ratio of the densities of the fluid feeding and leaving the channels provides accurate and stable predictions. Different discretization strategies were attempted. Besides the standard one made up with volumes of equal length (Fig. 7) another discretization was conceived. It was composed of volumes of linearly increasing length according to the local fluid velocity, with shorter volumes crossed by higher density fluid and longer volumes crossed by lower density fluid (Fig. 8).

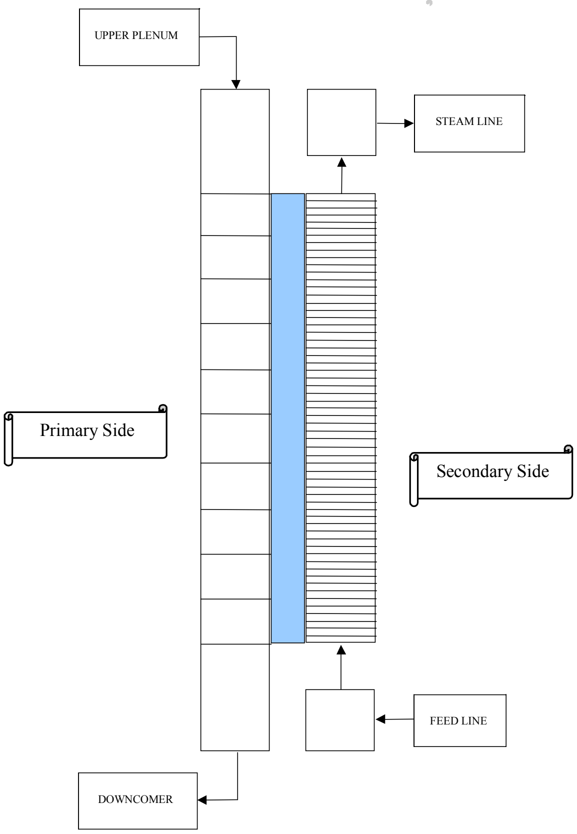

Figure 7. Standard Nodalization for 1-D system code (RELAP).

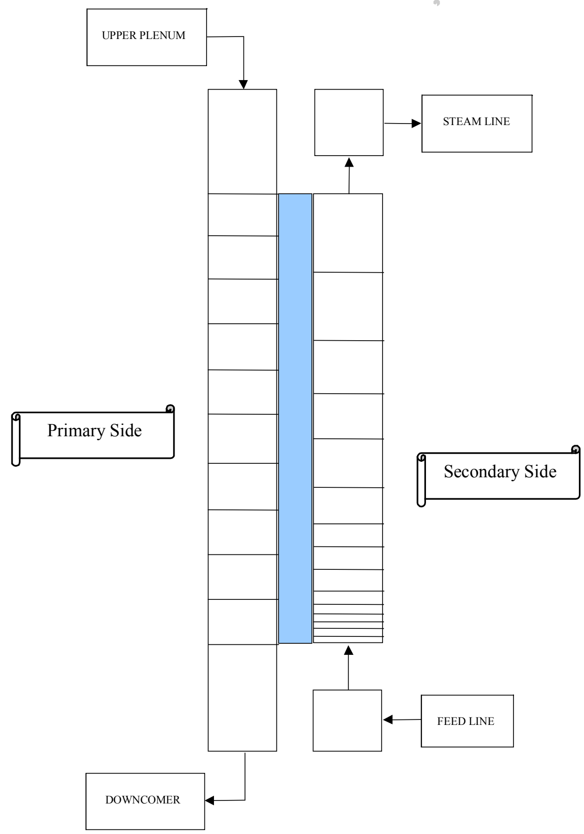

Figure 8. Improved Nodalization (Courant compliant) for the system code.

This latter strategy in numerical discretization comes from the adoption of a Courant criterion in order to limit the amplitude damping (numerical diffusion) and the frequency deformation (numerical dispersion). The Courant-Frederick-Levy number, defined as $CFL = a\ \Delta t/\Delta x$, where a is the local velocity, Δt is the time step and Δx is the space grid dimension, represent a stability criterion for the explicit part of the numerical scheme ($CFL \leq 1$) and assure a less diffusing-dispersing behavior when unity is approached. Therefore a space discretization for the Steam

Generator secondary side according to such a rule was tested. No appreciable difference arises between the predictions of steady-state configuration obtained with this improved nodalization and the standard one, with the advantage that the adoption of such a strategy means the halving of the run time, adopting the same number of volumes. Anyway the improved nodalization, being tailored on a particular steady-state flow condition, is less flexible than the standard one in the transient conditions.

2.3. Parallel Channels Stability

A thorough analysis of channel to channel interaction cannot rely only on modeling and numerical simulation but needs a solid and dedicated experimental basis, in order to get a deep understanding of the system dynamics and to ascertain the capabilities of the computing programs selected for the analysis. A thorough experimental campaign for the IRIS steam generator is currently being planned. In preparation to analyzing the experimental data, the possible numerical instabilities of the analytical codes are under investigation.

At this stage, the 1-D time domain system code RELAP was used. Both standard and improved nodalizations were used, with no significant difference in their predictions. In instability analyses, the advantage of improved nodalizations with regard to run time is less evident than in steady state. In fact, instability predictions, as a rule, cease to be discretization and time step dependent provided a high number of volume is used, roughly an order of magnitude greater than the number needed for stable analysis. Provided a proper nodalization is implemented, the predictions appear reasonable and compare favorably with expectations.

In order to evaluate the capability of the 1-D system code to predict instability behavior of the component, an unstable system of two unorificed channels was simulated with the RELAP code. An imposed temperature boundary condition is needed to evaluate the coupling between them. The system is started from cold conditions and is gradually heated and left free to reach a steady state. No stable state was reached, rather the system reaches and maintains an unstable, oscillating steady state condition. The two boiling channels oscillate out of phase, as expected for such a system. Amplitude and frequency are consistent with expectations. As it can be seen in Figure 9, an orifice placed at the inlet of the two channels gradually stabilizes the system.

In table II the results of a time step and nodalization analysis for the two coupled channels simulation are presented. As can be seen, the predictions do not depend on the time step selection, thus supporting the validity of the nodalization.

3. CONCLUSIONS

The following conclusions have been drawn from the preliminary analysis conducted so far:

- Satisfactory preliminary results can be obtained by relying exclusively on existing and validated computing tools. At this stage, neither the upgrade of existing computing programs nor the development of new and dedicated ones appears necessary and can be postponed to the final design.

- The system code RELAP and the CFD computing program FLUENT were selected for the preliminary analysis. Improved RELAP nodalization can be used to speed up the analysis without any appreciable loss of accuracy, in both steady and transient state.
- A thorough analysis of channel to channel interaction cannot rely only on modeling and numerical simulation but needs a solid and dedicated experimental basis, in order to get a deep understanding of the system dynamics and to ascertain the capabilities of the computing programs selected for the analysis. From preliminary analysis, RELAP capabilities toward coupled channels simulation appear promising.

Table II. Analytical capability of modeling an instable behavior (Oscillations Amplitude). Effect of nodalization and time step selection.

Number of Volumes	Time Step [ms]	Oscillations Amplitude for Inlet Mass Flow Rate [% of nominal]
50	20.0	≈ 0
100	10.0	≈ 30
100	5.0	≈ 28
100	2.0	≈25
200	5.0	≈ 500
200	2.5	≈ 500
200	1.0	≈ 500
200	0.5	≈ 500

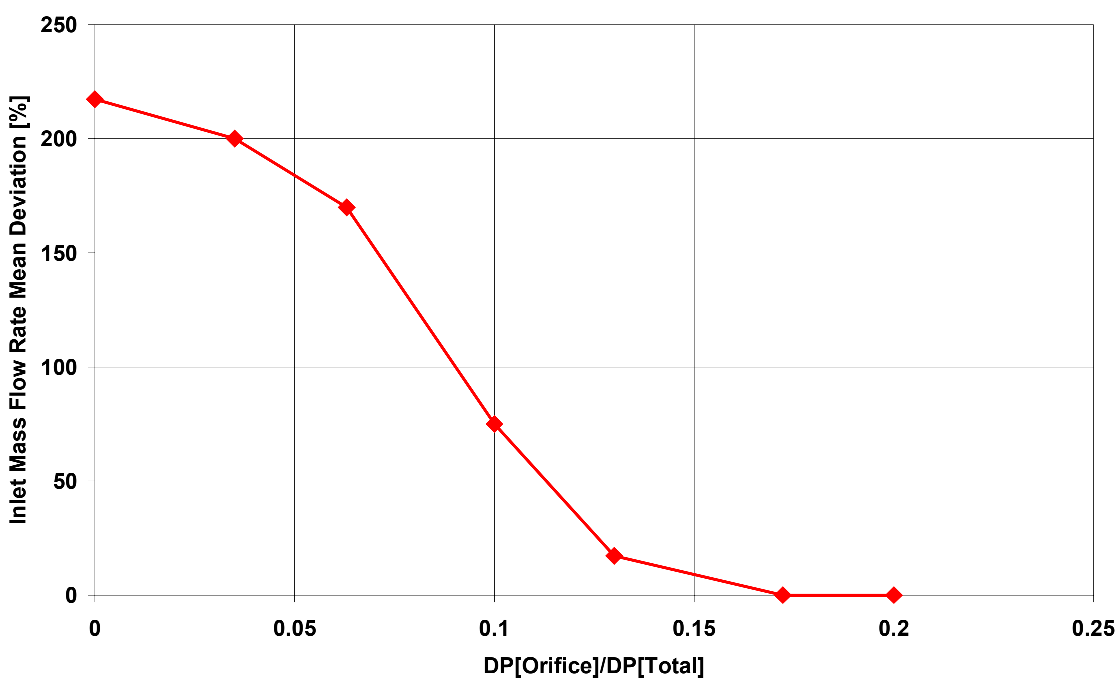

Figure 9. Inlet Orifice Stabilizing Effect

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